A fountain of molten rock hundreds of feet high sends rivers of lava flowing down the slopes of Kilauea in Hawaii.
Douglas Peebles

Ancient Floods of Fire

Today's volcanic eruptions pale in comparison with those in the geologic past that sent seas of lava across the earth

by Robert S. White

For almost a week, severe earthquakes had rocked southern Iceland. Then, on the morning of June 8, 1783, the ground southwest of Mount Laki split open along an eight-mile stretch. Incandescent fountains of lava erupted from dozens of vents along the fissure, spewing molten rock at a rate surpassing the flow of water over Niagara Falls. The landscape of green grasses disappeared beneath a blanket of fiery, reddish orange rock, which rapidly acquired a crust of black basalt as it cooled. The lava moved down the valley of the Skaftá River, advancing as much as nine miles in a single day. When the glowing rock emerged from the confines of the narrow valley four days later, it spread across the flat terrain near the coast. On July 29, the fissure extended another seven miles on the other side of Mount Laki, nearly tearing the dormant volcano in half. Lava spilled from the new break and filled another river valley before activity ceased the following February.

For the Icelanders, the Lakagigar eruption—the largest single outpouring of lava in historic times—was catastrophic. More than 200 square miles were buried beneath three cubic miles of fresh rock, but the lava caused no loss of life as it slowly overran two churches and forty-four farms. The gases released during the eruption, however, had disastrous consequences. That summer and autumn, a thick, bluish haze of sulfur dioxide and other volcanic gases settled over the country, blocking sunlight and stunting grass growth. With insufficient food and fluorine poisoning from the volcanic gases, roughly three-quarters of the country's livestock died, precipitating the Haze Famine, in which 10,000 Icelanders—a quarter of the population—perished. The haze reached eastward to Europe, causing the winter of 1783–84 to be particularly severe. Benjamin Franklin, who was in France at the time, noted the haze and suggested that the fine ash and gases from the Lakagigar eruption had prevented sunlight from warming the continent to its normal temperatures.

Despite its enormity, the Lakagigar eruption was minor compared with the massive outpourings of lava that have flowed from the earth in the geologic past. Half a dozen times during the last 200 million years, molten rock has erupted in such quantities that it left behind flood basalts, extraordinary formations of thick lava flows stacked thousands of feet high. Volcanism on this scale has no modern counterpart; the last episode, which ended about 15 million years ago, left large areas of Washington, Oregon, and Idaho buried beneath the Columbia River flood basalts.

One of the largest of these volcanic episodes occurred 66 million years ago, when molten rock that poured from a rift on the western coast of India covered a third of the peninsula with 500,000 cubic miles of lava. This geologic province is called the Deccan Traps because the hundred or so individual flows exposed by erosion resemble giant steps (*deccan* is from the Sanskrit for "southern," and *trap* is Dutch for "staircase"). Single layers containing a thousand times the volume of rock that erupted from the Lakagigar fissure can be traced across the region. Within half a million years—a blink of the eye in geologic time—molten rock had spread in thick sheets across the landscape until parts of it were buried beneath a mile and a half of new rock.

The tremendous volume of fine dust, carbon dioxide, sulfur dioxide, and other gases that escaped from the earth's interior during these eruptions must have had dramatic effects on the planet's climate. Widespread acid rain and prolonged darkness could have killed vegetation over much of the planet, disrupting food chains. The acidity of the oceans might also have been raised, endangering microscopic organisms. Because the age of the Deccan Traps coincides with the extinction of the dinosaurs and countless other species at the end of the Cretaceous, some scientists believe that the large outpourings of lava contributed to the catastrophe. But the link between the two events has been hard to prove. Others argue that if these extraordinary eruptions of lava had such dire consequences for life on earth, geologists and paleontologists should be able to match other mass extinctions with eruptions of flood basalts. So far, the timing of many of these events is sufficiently uncertain to prevent us from drawing firm conclusions about their simultaneity.

In the early 1970s, J. Tuzo Wilson, a geologist at the University of Toronto and one of the pioneers of plate tectonics, noticed that ancient flood basalts are often associated with the tracks of hot spots, localized regions of current volcanic activity. The challenge for me and my colleagues at the University of Cambridge was to explain how the two features are related and why flood basalts are such rare events. The answers came only after we refined our picture of how processes deep within the mantle shape the earth's surface.

Before we could account for flood basalts, we needed to understand the less spectacular, but continual, bleeding of basalt taking place beneath the sea along the

A break in the wall of a Hawaiian lava tube offers a glimpse of the torrent of rock flowing within. Such conduits form when basalt cools and hardens on the surface of a lava flow.
Dorian Weisel

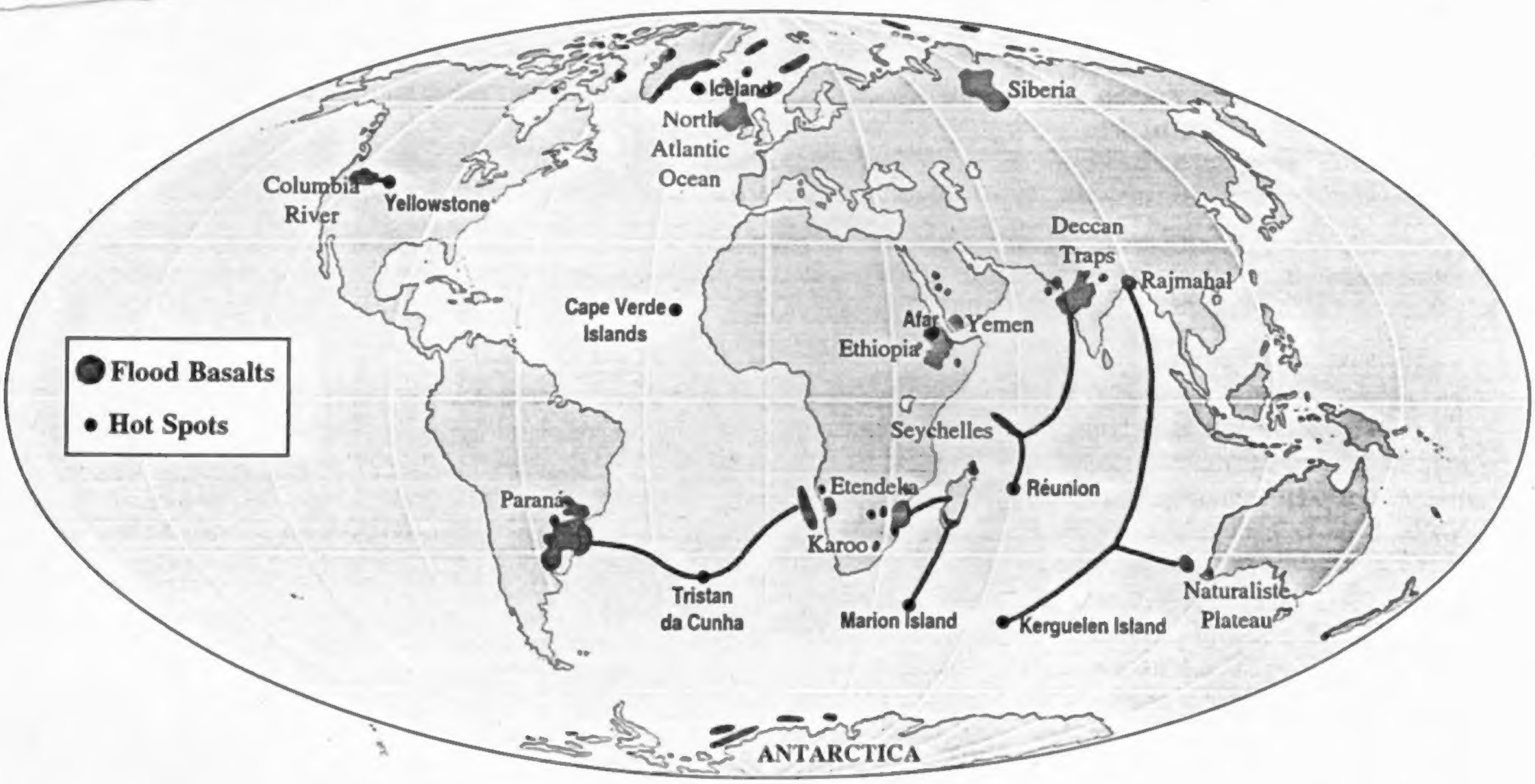
30,000 miles of oceanic rifts that circle the globe. In total volume, this volcanism is more important than the flood basalts, producing almost five cubic miles of new igneous rock each year—enough to build all the oceanic crust, which has been completely renewed during the last 200 million years. On the other hand, compared with flood basalts these submarine eruptions have little effect on the atmosphere because almost all of them occur deep underwater and the individual eruptions are much smaller.

The lava erupting at oceanic rifts originates in the asthenosphere, the ductile mantle that lies sixty miles below the earth's surface. At this depth, tremendous pressures inhibit mantle melting, despite temperatures of more than 2000° F (just as a pressure cooker prevents water from boiling at its normal temperature). Under certain circumstances, however, the mantle rock can move upward toward the surface. Above the ductile mantle, the dozen or so plates of the lithosphere, the earth's rigid outer skin, are in constant motion. At oceanic rifts, where the plates pull apart at rates of a few inches per year, the ductile mantle wells slowly upward to fill the gap. For every ten feet that the mantle rises, the pressure falls by approximately one atmosphere (or about 14.7 pounds per square inch, the pressure that the atmosphere exerts on us at sea level). Halfway up, at a depth of about thirty miles, the pressure falls sufficiently to allow melting to start. Here, a tiny fraction of the mantle rock liquefies. More and more of the mantle melts as it approaches the surface and continues to decompress. By the time the mantle has reached the base of the oceanic crust, about 25 percent of it has melted. The molten rock is very buoyant and percolates rapidly upward until it solidifies near the surface and becomes new crust. Less than a quarter of the magma erupts onto the sea floor as lava.

This simple model of decompression melting of the mantle explains the generation of the entire oceanic crust, which covers more than two-thirds of the globe. In laboratories around the world, researchers have tried to replicate the extremes of temperature and pressure at which mantle

David Jensen

A prickly pear cactus emerges between columns of basalt in eastern Oregon's Hell's Canyon, left. The hexagonal pattern of the columns formed when a thick lava flow in the Columbia River flood basalts slowly cooled and cracked. The world's major flood basalts are shown on the map below. In many cases they can be linked with hot spots that were once beneath them.
Joe LeMonnier



rock melts. Their experiments appeared to yield disparate results until Dan McKenzie and Michael J. Bickle, of the University of Cambridge, sifted through the data and plotted melting curves that brought the findings into agreement. They were the first to figure out exactly how much melt would be produced as the ductile mantle welled up under rifts.

Their model not only explains the thickness and composition of oceanic crust but also shows that the amount of melting is extremely sensitive to the temperature of the parent mantle. Measurements of the oceanic crust around the world have shown that its thickness varies remarkably little: it is about four miles thick everywhere. To produce this volume of basalt, the average mantle temperature immediately beneath the lithosphere must be 2440° F, varying by less than 40° F over most of the world.

At the same time that McKenzie and Bickle were formulating their mantle-melting model, Emily M. Klein and Charles H. Langmuir, of the Lamont-Doherty Geological Observatory of Columbia University, were reaching similar conclusions, but from another direction. After analyzing basalts dredged from midocean rifts around the world, they noted that the compositions of these rocks were directly related to the thickness of the crust. Temperature determines not only how much of the mantle will melt as pressure is reduced but also what the magma's chemical composition will be.

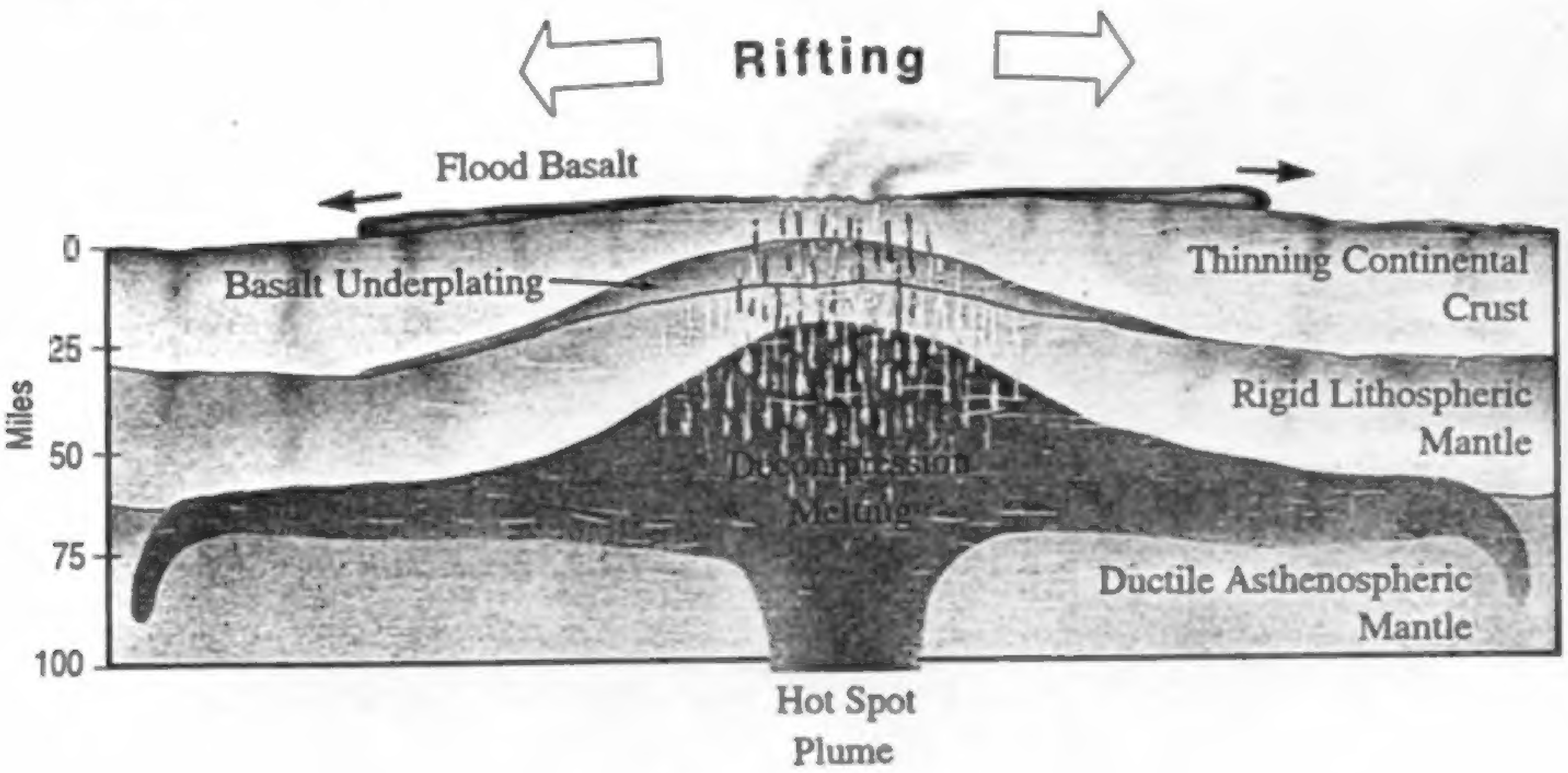
By 1987, we understood the main factors controlling the generation of basalt at midocean rifts, and our attention turned to rifts on the continental plates. Although continental crust is almost five times thicker than oceanic crust, the rigid lithospheric mantle beneath them reaches down to approximately the same depth. Thus, when a continental plate stretches, thins, and finally ruptures, the mantle welling up from below should decompress and partly melt exactly as it does beneath oceanic rifts. If the two halves of a rifted continental plate continue to separate, a new ocean basin forms, leaving continental margins on each side. In many cases, the thin edge of crust drops below sea level, forming a continental shelf. In 1979, a joint French–English expedition used seismic equipment towed behind a ship to obtain a profile of the continental margin west of France beneath the Bay of Biscay. (Seismic waves sent from the surface penetrate deep into the earth and are reflected back by the geologic layers. The resultant seismic images are fuzzy, but essential details of the underlying geology can be discerned.) The survey revealed the expected pattern: the twenty-two-mile-thick European continental crust stretches and thins over a distance of 140 miles until, where it is only four miles thick, it breaks and is succeeded by oceanic crust.

In late 1986, however, another survey farther north in the Atlantic Ocean yielded some very odd results that did not fit this simple picture. Using two British research ships, the *Charles Darwin* and the *Discovery*, we surveyed the continental margin west of the Scottish coast, where the Hatton Bank rises above the surrounding sea floor near the island of Rockall. Graham K. Westbrook, of Birmingham University, England, was the chief scientist on one ship, and I was in charge of the other with a team of scientists from Cambridge. The seismic data analyzed at Cambridge by Susan R. Fowler and George D. Spence showed

Jeff Gnass

Along the Bruneau River in southwestern Idaho, right, individual lava flows form the horizontal layers typical of flood basalts. The diagram below shows a cross section of the earth where a mantle plume rises beneath a rift. The heat of the plume and the decompression that occurs as rock rises beneath the rift result in both the huge flood basalts on the surface and the underplating of basalt below the crust.

Joe LeMonnier



that instead of thinning, this section of the continental crust actually thickens as it nears the edge. The thickening is caused by a ten-mile-thick wedge of basalt plated onto the bottom of the continental margin. Because it was clearly different from the overlying crust, we concluded that the wedge was added as a result of the rifting. The only possible source of the new rock was melt added from below. But what could account for its enormous volume?

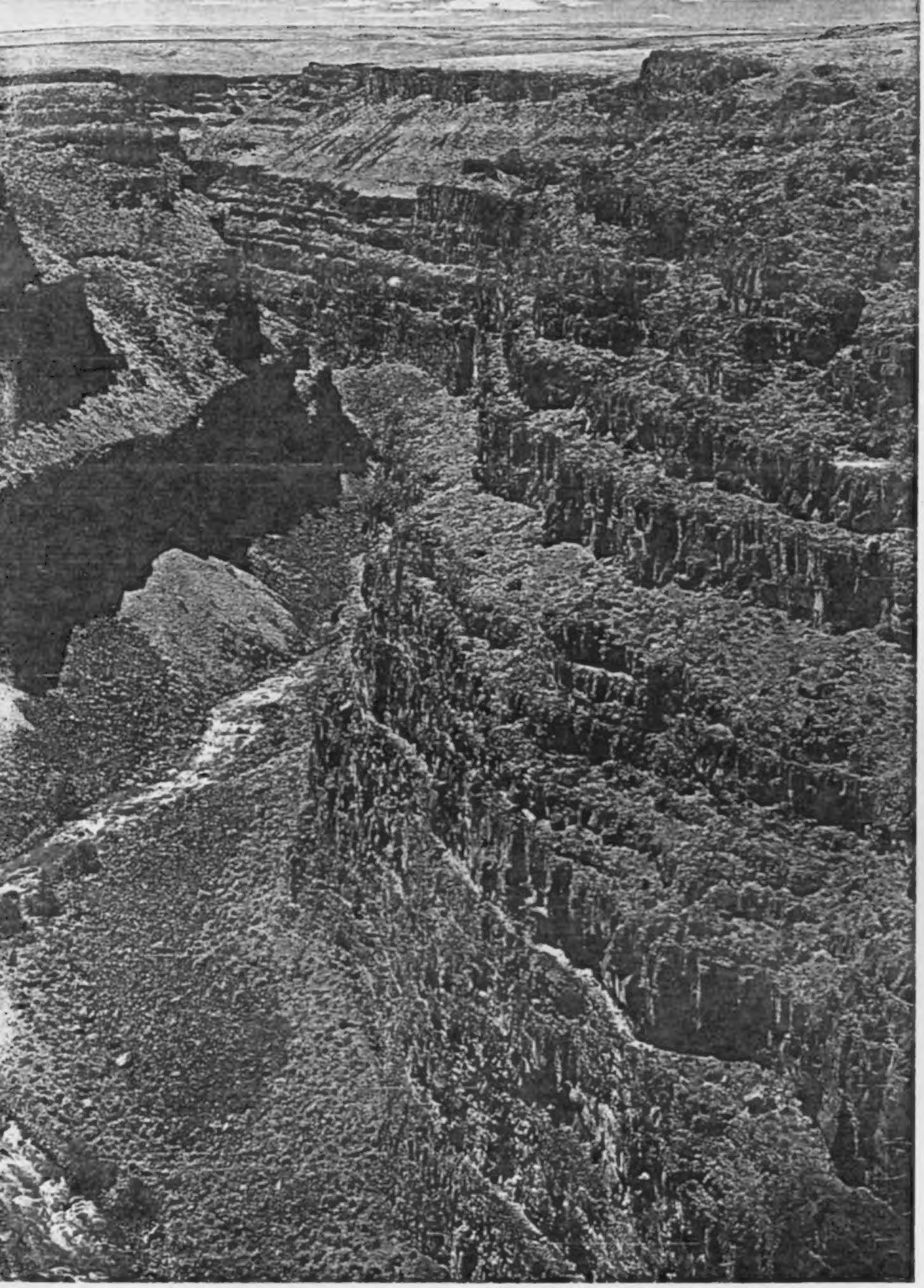
As we discussed the problem in the tea room of the Bullard Laboratories at Cambridge, Dan McKenzie brought out his first computer plots from the mantle-melting model. When we saw how sensitive the amount of melting was to temperature, we knew we might have the answer to how the wedge beneath Rockall had been formed. An increase of only 180° F (about 7 percent) in the temperature of the mantle would more than double the melt generated by decompression under a rift. A 360° F increase would quadruple the amount of magma rising into the rift. A temperature increase of only 250° F in the mantle would have produced the underplating we had observed. But we knew that mantle temperatures do not normally vary by even small amounts. What was the source of the additional heat?

The question was resolved by a separate line of research that was still fresh in our minds. In 1983 I had led a research team from Cambridge on a cruise to the area around the Cape Verde Islands in the Atlantic Ocean. These islands and others, such as Hawaii, Réunion, and the Azores, dot the world's oceans wherever intense volcanism has built mountains up to four miles high, reaching from the ocean floor to above sea level. In the early 1960s, geologists dubbed them hot spots to distinguish them from the chains of volcanic peaks marking certain plate boundaries. Because of their apparently random distribution, geologists assumed that hot spots were caused by abnormally hot rock welling up from deep within the mantle and had little to do with the vagaries of plate motions.

Using special deep-sea probes driven into the bottom sediments with 2,000-pound weights, we measured the heat being conducted upward through the sea floor. The interior of the earth remains extremely hot from its initial formation and the continuous decay of radioactive elements, even though it has been cooling for billions of years. The heat escapes through the earth's outer skin at a surprisingly high rate: on average, an area equivalent to four football fields continuously pumps out heat at a rate of one kilowatt (about the amount of energy used by a toaster), day after day, year after year, millennium after millennium. In the vicinity of the Cape Verde Islands, however, we found that the heat loss was 25 percent higher than normal and that the elevated heat loss extended over an area stretching 400 miles from the islands.

Two other observations pointed to an exceptionally hot mantle over a broad area. First, the sea floor was pushed up in a gentle, 900-mile-diameter submarine swell more than a mile high at the center, as if the underlying mantle had expanded. Second, satellites measured a gravitational anomaly above the swell, indicating a region of low density in the mantle. Both of these observations are what we would expect to see if the mantle below were hotter than normal.

Robert C. Courtney, then a graduate student at Cambridge, used a computer to model the rising plume of hot rock that would account for our observations around the Cape Verde Islands. In shape, the hot spot resembles a gigantic mushroom, the "cap" being a broad region immediately beneath the sea floor swell and the "stem" a relatively narrow column about 150 miles wide. About 450° F hotter than the surrounding mantle at its center, the column rises until it is deflected



sideways by the rigid lithosphere to form a huge head of bouyant mantle about a thousand miles in diameter. Instead of affecting only a limited area directly above the rising plume, hot spots elevate temperatures over a much broader region of the upper mantle.

Now we knew where the abnormally hot mantle that produced the wedge of basalt beneath Rockall came from—a hot spot. Iceland, which sits directly on top of the mid-Atlantic ridge almost a thousand miles to the northwest of Rockall, owes its existence to a plume that continuously delivers abnormally hot mantle directly under the rift. When the North Atlantic opened up some 57 million years ago, however, the continental margin west of Rockall would have been above the mushroom head of the Icelandic plume. The additional heat beneath the rifting continents would have caused the decompression melting of the mantle at a rate far exceeding that of mantle at normal temperatures and produced a tremendous volume of magma along the rift—enough to emplace basalt beneath the stretching continental crust and erupt flood basalts onto the surface.

We had found the basalt beneath Rockall, and others had discovered a similar underplating of the crust off the coast of Norway, but where were the massive outpourings of lava? In India, the Deccan flood basalts are clearly visible, forming a high plateau, but in the North Atlantic, the continental margins have sunk beneath sea level, hiding their geology. With seismic surveys, however, we could see what was there. Near Rockall, we found lava flows up to several miles thick, extending as far as 100 miles toward Scotland from the edge of the continental crust. Additional seismic profiles revealed massive lava flows along more than a thousand miles of the rifted margins on both sides of the northern Atlantic. From the eastern margin of Greenland to the northwestern margin of Europe, the flood basalts turned up wherever the North Atlantic rift opened above the mushroom head of hot mantle surrounding the Icelandic plume. Until a few years ago, no one suspected massive lava flows there at all, but their total volume is an astonishing half million cubic miles—just as much as in the Deccan flood basalts.

Once we realized that a hot spot beneath rifting continents could explain the massive outpourings of lava along the margin of the northeastern Atlantic, we looked to other flood basalts around the world to see if they supported our model of mantle decompression. Fortunately, a great deal of work had previously been done on flood basalts against which we could test our ideas. In each case we found evidence that flood basalts were associated with continental breakup above a hot spot. For example, the Deccan Traps were formed as the Seychelles fragment (a piece of continental crust now largely submerged beneath the Indian Ocean) split away from mainland India. Since the breakup, the Indian plate has drifted northward, so that the hot spot that was once under the rift is now 3,000 miles south of India, below Réunion. As the plate crept along, the melt generated by the central plume of the hot spot produced a trail of extraordinarily thick oceanic crust, forming the Laccadive-Chagos volcanic ridge and the Mascarene Plateau, features that lead directly from the Deccan Traps in western India to the culprit's present location.

When the African and South American continents split apart about 130 million years ago to form the South Atlantic, two huge flood basalt provinces developed on either side of the rift. Massive melting of the mantle poured up to half a million cubic miles of basalt onto the South American mainland, creating what is now known as the Paraná flood basalt, named after the river that flows across it. Across the ocean, flood basalts of the same age are found in Namibia. As the South At-

An eruption on Réunion launches thousands of lava bombs into the night sky. The hot spot below Réunion produced the Deccan flood basalts 66 million years ago.
Krafft/Explorer; Photo Researchers, Inc.

lantic opened between the continents, the hot spot continued to send magma to the surface, leaving thick volcanic features, known as the Rio Grande Rise and the Walvis Ridge, on the sea floor. These two trails lead from the flood basalts to the hot spot lying under the volcanic island of Tristan da Cunha, whose entire population was evacuated in 1962 because of renewed eruptions.

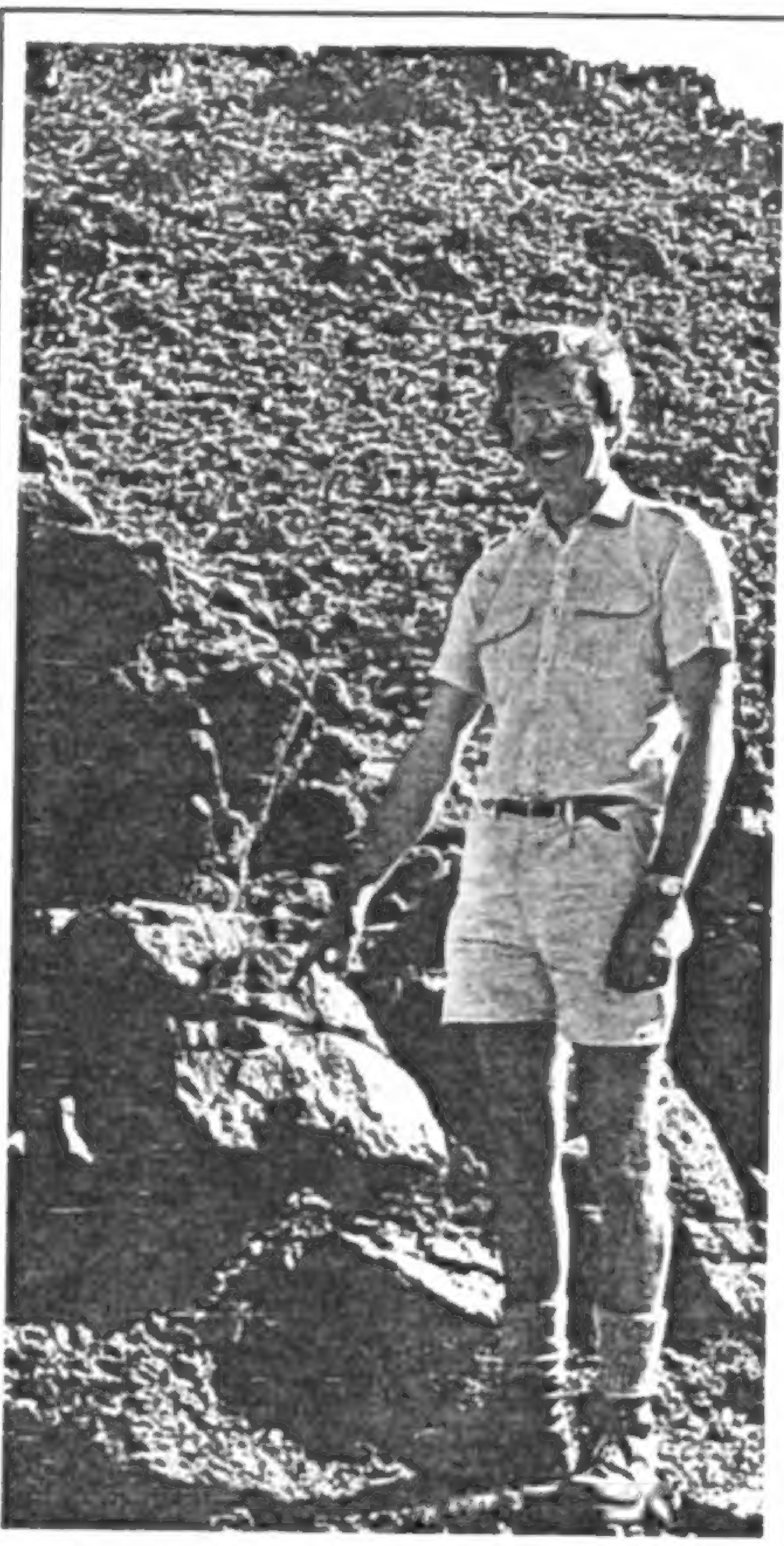
As McKenzie and I refined our model, another puzzling feature of flood basalts began to make sense. Before breaking up, the lithosphere stretches, normally causing the terrain to subside (as it has in the oil-rich sedimentary basin of the North Sea east of Britain). But flood basalts form above sea level; and instead of being confined to narrow valleys, the lava spreads out in sheets extending hundreds of miles away from the main fissure. As at the Cape Verde Islands, a hot spot is capable of uplifting a broad region by as much as a mile. This doming effect, as well as the plating of igneous rock on the base of the stretching crust, counteracts the subsidence normally accompanying rifting. The terrain surrounding a continental rift above a hot spot is actually elevated, so that the basalt simply pours downhill on either side as fast as it erupts. Keith G. Cox, a geologist at Oxford University, noticed that the uplifted continental crust over these hot spots is reflected by odd river-drainage patterns around the world. For instance, in a broad region to the west of São Paulo, Brazil, where the Paraná flood basalts are found, the rivers all flow away from the Atlantic coast. Similarly, the rivers in western India, instead of making their way directly to the nearby sea, flow to the east in a radial pattern away from the coast and Bombay, where the hot spot that produced the Deccan Traps was centered.

Hot spots may also play a large role in breaking up the continents. From the size of the flood basalt provinces around the world, we concluded that most of them were formed as rifts opened above new hot spots. Although hot spots remain more or less fixed in the mantle for millions of years as the plates drift about, they are not permanent. A new plume forms when

Fingers of highly fluid lava, called pahoehoe, spread outward from a flow on Hawaii. A thin, elastic skin forms rapidly around the molten rock as it cools.
Jack Jeffrey

rock deep within the mantle grows hotter—and less dense—than the surrounding material and eventually becomes unstable and begins to rise. When a hot spot is born deep within the mantle, an initial, large blob of mantle pushes toward the lithosphere at a relatively rapid rate; then, over millions of years, it continues to be fed by a narrow plume like the one beneath the Cape Verde Islands that we modeled. We estimated that the initial mantle blob that produced the volume of magma found in the flood basalts of the North Atlantic, India, and Brazil must have been at least 100° F hotter than the subsequent, steady flow. The rapid uplift caused by a new plume pressing against an overlying plate may contribute to the stresses causing continental breakup. For example, stretching and rifting of the continental crust occurred between Greenland and northern Europe for tens of millions of years prior to their breakup; but only after the arrival of the Icelandic plume 60 million years ago did rifting proceed far enough for the North Atlantic to begin opening up.

McKenzie and Bickle's simple model of how the mantle melts explains with remarkable success a number of the earth's seemingly unrelated features. The same physical laws that govern the continuous production of oceanic crust covering two-thirds of the globe also dictate where and when eruptions of flood basalts will occur. Although the underlying processes remain constant, their results are often far from uniform. Every now and then, amid the chaos of plate tectonics and the seething mantle below, a rising plume and a continent prone to rifting will coincide, and lava will flood another part of the world. Fortunately, this is infrequent, and during humanity's brief existence we have been spared. The future, however, undoubtedly holds more catastrophic eruptions of flood basalts with long-term consequences far worse than those of Iceland's 1783 eruption. More than two hundred years ago, James Hutton, a Scottish geologist, recognized that human history holds no special place in the vastness of geologic time. He wrote that "we find no vestige of a beginning,—no prospect of an end." □



Standing in the desert in Oman, **Robert S. White** (page 50) points to the base of a slab of oceanic crust, which was shoved onto land when an ancient sea was caught between the earth's shifting plates. The site is one of the few places where geologists can observe oceanic crust from top to bottom. White has devoted most of his career to studying such crust, which forms two-thirds of the earth's surface. He went to the University of Cambridge as an undergraduate to study physics, but his love of the outdoors and the attraction of studying the geology hidden beneath the oceans (which was still largely unexplored) won him over to the subject of geophysics. Currently a geophysicist at Cambridge, White continues to study the earth's crustal structure and the interplay between tectonics and magmatism. For further reading, he recommends Robert and Barbara Decker's book, *Volcanoes* (San Francisco: W. H. Freeman and Company, 1989).